Floods, droughts and climate variability

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Chapter 2

The role of climate variability in extreme floods in Europe

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Abstract

Climate variability is shown to be an important driver of spatial and temporal changes in hydrometereological variables in Europe. However, the influence of climate variability on flood damage has received little attention. We investigated the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the East Atlantic pattern (EA) during their neutral, positive, and negative phases, to understand their relationships with four flood indicators: Occurrence of Extreme Rainfall, Intensity of Extreme Rainfall, Flood Occurrence, and Flood Damage. We found that positive and negative phases of NAO and EA are associated with more (or less) frequent and intense seasonal extreme rainfall over large areas of Europe. The relationship between ENSO and the Occurrence of Extreme Rainfall and Intensity of Extreme Rainfall in Europe is much smaller than the relationship with NAO or EA, but still significant in some regions. We show that Flood Damage and Flood Occurrence have strong links with climate variability, especially in southern and eastern Europe. Therefore, when investigating flooding across Europe, all three indices of climate variability should be considered. Future research should focus on their joint influence on flood risk. The potential inclusion of seasonal forecasts of indices of climate variability could be effective in forecasting flood damage.

2.1 Introduction

Between 1980 and 2015, Europe experienced 18% of worldwide weather-related loss events, which accounted for over US$500 billion (bn) in damage (Munich Re, 2016b). Consequently, it is urgent to further develop adaptation strategies to mitigate the consequences of weather-related disasters, such as floods (Jongman et al., 2014). Europe’s capability to prepare for such disasters is challenged by a large range of uncertainties and a limited understanding of the driving forces of hydrometeorological hazards (Apel et al., 2004). One of the major sources of uncertainty is the relationship between climate variability and weather-related losses (Merz et al., 2014).

Climate variability refers to natural fluctuations of the climate system around the long-term trend (Stocker et al., 2013). Such variability is caused by coupled interactions between atmospheric and oceanic components, measured by an index. Globally, ENSO is the most important mode of climate variability, and has been linked with changes in hydrometeorological extremes in past studies at different scales, including national (Rios-Cornejo et al., 2015; Sun et al., 2014; Villafuerte et al., 2014), continental (Cannon, 2015; Casanueva et al., 2014; Ionita et al., 2015), and global (Sun et al., 2015; Veldkamp et al., 2015; Ward et al., 2010, 2014).

In addition to ENSO, hydrometeorological variables across Europe show relationships with other indices of climate variability, such as the NAO and EA. NAO measures anomalies in sea level pressure over the subpolar and the subtropical region of the North Atlantic (Hurrell et al., 2003), while the EA measures these anomalies across the entire North Atlantic region from east to west (Barnston & Livezey 1987;NOAA 2017). ENSO, NAO, and EA have positive, negative, and neutral phases, and can be related with variations in the European climate. For instance, an NAO^+ phase links with increased westerlies over the middle latitudes, and intense weather systems over the North Atlantic. On the other hand, NAO^- phase shows an opposite pattern over these regions (Hurrell et al., 2003). Therefore, different phases of ENSO, NAO and EA can be associated with increases or decreases in disaster burden (Goddard & Dilley, 2005; Mitchell et al., 2017; Pinto et al., 2009) .

Whilst several studies have assessed the regional influence of ENSO, NAO, and EA on precipitation (Goddard & Dilley, 2005; Gregersen et al., 2013; Lopez-Bustins, Martin-Vide, & Sanchez-Lorenzo, 2008; Lorenzo, Taboada, & Gimeno, 2008; Mariotti, Zeng, & Lau, 2002; Rodó, Baert, & Comin, 1997) and discharge (Markovic & Koch, 2014; Struglia, Mariotti, & Filograsso, 2004), less research has been carried out at Pan-European scale. Fewer still have examined peak discharge. An exception is an investigation of observed European peak river discharge relationships with NAO, Arctic Oscillation (AO), frequency of west circulation (FWC), and north to south sea level pressure difference (SLPD) (Bouwer et al., 2008). Some studies have examined climate variability's influence on extreme precipitation (Casanueva et al., 2014). However, these studies do not address differences in the frequency and intensity of extreme precipitation during positive and negative phases compared to neutral phases.

Only few studies specifically addressed relationships between climate variability and the socioeconomic impacts of flood disasters. At the global level, an initial study (Dilley & Heyman, 1995) assessed links between ENSO and the reported frequency of drought and flood disasters. Subsequently, others (Bouma et al., 1997) investigated links between El Niño and the burden on human health. These studies were followed up by research (Goddard & Dilley, 2005) that analysed whether phases of ENSO could be associated with an increase in reported climate-related disasters. Recently, a global flood risk model was used to examine ENSO's relationship with flood risk at the global scale (Ward et al., 2014), while other studies have assessed relationships between NAO and EA and agriculture risks e.g. (Brown, 2013; Cantelaube, Terres, & Doblas-Reyes, 2004; Fuhrer et al., 2006; Hernández-Barrera & Rodríguez-Puebla, 2017; Irannezhad, Chen, & Kløve, 2016).

To the best of our knowledge, no studies have examined the impacts on flood damage of multiple indices of climate variability. Therefore, we analyse ENSO, NAO, and EA indices during their neutral, positive and negative phases, to answer the following research questions:

- Are there differences in the frequency and intensity of extreme rainfall between the different phases of the indices of climate variability?
- Are there anomalies in flood occurrence and damage between the different phases of the indices of climate variability?

In section 2.2 we describe the climate and flood indicators, and the statistical methods, followed by the presentation and discussion of the results in sections 2.3 and 2.4. We conclude with section 2.5.

2.2 Methods: climate and flood indicators and statistical approach

We use statistical methods to analyse relationships between ENSO, NAO, and EA indices and four indicators of flooding, namely: (1) Occurrence of Extreme Rainfall (OER); (2) Intensity of Extreme Rainfall (IER); (3) Flood Occurrence; and (4) Flood Damage. These indicators were derived from two datasets: a database of flood disasters and losses in Europe (Munich Re, 2016a) and a gridded dataset of daily precipitation (Haylock et al., 2008). An overview of the methodological framework is displayed in Figure 2.1. The methods and datasets are described in more detail in the following subsections.

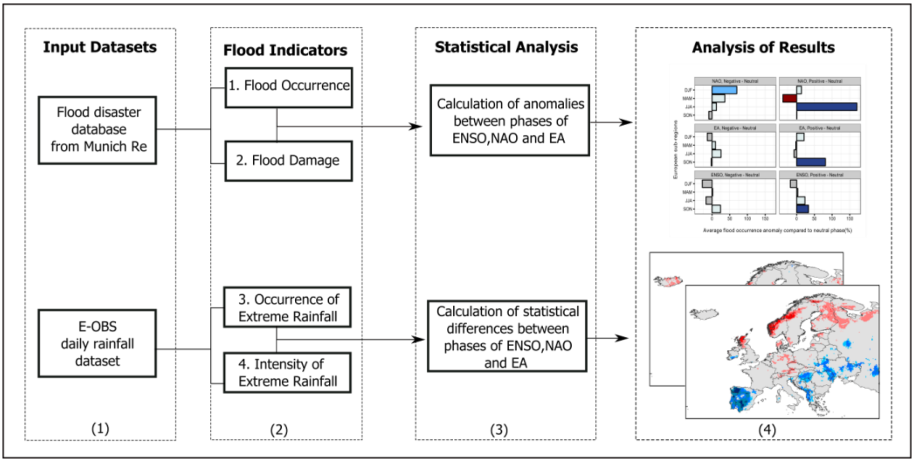

Figure 2.1 Flowchart representing the methodological framework applied in this study, handled in four steps: (1) collection of two input datasets; (2) extraction of four flood indicators based on input datasets; (3) application of statistical methodology; (4) analysis of results.

2.2.1 Indices of climate variability

In this study, we represent climate variability using the ENSO, NAO and EA indices, whose phases were divided into negative, positive and neutral.

For ENSO, we used the Oceanic Niño Index (ONI) from 1950-2014 (http://www.cpc.ncep.noaa.gov). ONI is a three-months running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region. We used the data for December-February (DJF), March-May (MAM), June-August (JJA), and September-November (SON). ENSO's phase classification was established by the National Oceanic and Atmospheric Administration (NOAA), which compares the running mean value to a 30-year average to derive periods of below or above normal SSTs. $ENSO^-$ ($ENSO^+$) phases are classified when the threshold of – (+) 0.5°C is met for a minimum of five consecutive overlapping 3-month periods.

For NAO, we used the Hurrell NAO index (station-based) from the Climate Data Guide (https://climatedataguide.ucar.edu/climate-data). We obtained the seasonal index from 1950-2014 for DJF, MAM, JJA, and SON. For EA, we used the monthly standardized index from NOAA. Again, we averaged the EA series for the same period as for NAO. Both the NAO and EA indices follow a Gaussian distribution, therefore, the three phases were classified using a ± 1σ (Jeong &

Ho, 2005). An overview of the indices and their classification is shown in the appendix Figure A1.

2.2.2 Flood indicators and European sub-regions

We assess flood by means of four indicators: OER, IER, Flood Occurrence and Flood Damage. Because Flood Occurrence and Flood Damage records were not sufficient to establish comparison at the country level, we grouped the records into four sub-regions. For the European sub-regions (appendix Figure A2), we used the classification established by the United Nations Statistics Division. We extracted all four indicators seasonally: winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

2.2.2.1 Occurrence of Extreme Rainfall and Intensity of Extreme Rainfall

We obtained the OER and IER from the E-OBS rainfall dataset (http://www.ecad.eu/). This dataset contains daily gridded precipitation for 1950-2014, with a horizontal resolution of 0.25 degree. We extracted the OER events per season and year, and the intensity of those events. We define extreme rainfall using Partial Duration Series (Coles et al., 2001), where the n largest rainfall events are extracted per year, relative to the length of the daily series (Prudhomme & Genevier, 2011). The extreme series contain an average of three high rainfall events per season (n = 3×65 years). We applied an inter-event time criterion of 24 hours to fulfil the independence of the series, and calculated the OER by counting the number of extremes per season/year; the indicator of IER is the ratio of the sum of the intensity of these respective events (per season/year) and the OER indicator.

2.2.2.2 Flood Occurrence and Flood Damage

We used the NatCatSERVICE dataset of Munich Re (Munich Re, 2016a) to derive time-series of Flood Occurrence and Flood Damage. This dataset registers flood events in Europe, and their respective period, timing, location and damages (US$) between 1980-2012. To calculate Flood Occurrence we extracted the initial date of the floods, and then counted and sorted these events into a specific season of the year. For the Flood Damage indicator, we deflated the nominal flood damage recorded from 1980-2012 into 2010 US$ values, and converted these into Purchasing Power Parity (PPP) equivalent (further description in the Appendix A3). The distribution of reported flood events and damage recorded in the Munich Re database per sub-region and season is available in Figure A3.

2.2.3 Statistical approach

For the OER and IER indicators, we applied a two-tailed T-Test (each tail α=5%). The test identifies whether the mean occurrence and intensity of extreme rainfall found in positive or negative phases are significantly different from the one found during the neutral phase. Field significance of the gridded results was assessed using the binomial distribution (Livezey & Chen, 1983).

For the Flood Occurrence and Flood Damage indicators, we used a methodology proposed in previous research (Iizumi, Luo, et al., 2014). Following this approach, we investigated anomalies in Flood Occurrence and Flood Damage within phases of ENSO, NAO and EA by calculating the percentage anomaly that deviates from a normal value (defined as 5-years running mean) for the time interval (t in years) $t-2\ to\ t+2.$ We applied a 5-years running mean to minimize possible pitfalls regarding reporting issues in the Munich Re dataset. Often, an issue with disaster databases is that the frequency count of damaging floods includes increased reporting of disasters towards more recent years (Merz et al., 2012). In addition, we tested the long-term average (1982-2010) as a normal value, however results did not greatly differ between the two methodologies (appendix A4). The percentage anomaly (F') for a respective season (*S*) and sub-region (*R*) is obtained by:

$$F'_{S,R} = \frac{F_{S,R} - \overline{F}_{S,R}}{\overline{F}_{S,R}} \times 100 \qquad \text{Equation 2.1}$$

$F_{S,R}$ indicates the value of the Flood Occurrence or Flood Damage, and $\overline{F}_{S,R}$ is the normal value for the indicator. The calculation of the percentage flood anomaly aims to detect the major changes in these two indicators induced by short-term climate factors, although other factors like exposure and vulnerability may also contribute to yearly variations. The second step is to obtain an average flood anomaly (%) for each phase of the climate indicator *(I)* for 1982-2010:

$$F'_{R,I^+} = \frac{1}{n_{I^+,\ R}} \sum_{1982}^{2010} F'_{S,R}\ if I_S \geq u \qquad \text{Equation 2.2}$$

$$F'_{R,I^-} = \frac{1}{n_{I^-,\ R}} \sum_{1982}^{2010} F'_{S,R}\ if I_S \leq -u \qquad \text{Equation 2.3}$$

$$F'_{R,I^N} = \frac{1}{n_{I^N,\ R}} \sum_{1982}^{2010} F'_{S,R}\ if\ -u < I_S < u \qquad \text{Equation 2.4}$$

$n_{I^+,R}$, $n_{I^-,R}$ and $n_{I^N,R}$ are the numbers of positive, negative and neutral phases of indices of climate variability, respectively, and threshold u is $\pm 1\sigma$ or ± 0.5°C depending on the climate indicator. Next, we compared the difference between average percentage flood anomalies in positive or negative seasons to the values in neutral seasons:

$$\Delta F'_{R,I^+} = F'_{R,I^+} - F'_{R,I^N} \quad \text{Equation 2.5}$$

$$\Delta F'_{R,I^-} = F'_{R,I^-} - F'_{R,I^N} \quad \text{Equation 2.6}$$

A negative (positive) value of $\Delta F'_{R,I^+}$ and $\Delta F'_{R,I^-}$, suggests, on average, a lower (higher) impact of the index of climate variability I^+ and I^-, compared to the average in flood anomaly for the indicators in neutral phases. We tested the statistical significance of the difference by bootstrapping the values of the percentage flood anomaly for a sub-region using 10,000 iterations. The two-sided test considers significance level of 5% (strong significance) and 10% (weak significance) in each tail, adopting the null hypothesis that the difference between the average percentage flood anomaly in I^+ or I^- and I^N are equal to zero (details in the Appendix A5).

2.3 Results

In this section, we firstly describe the differences in OER and IER indicators within ENSO, NAO and EA phases, followed by outcomes regarding anomalies in Flood Occurrence and Flood Damage.

2.3.1 Differences in the Occurrence and Intensity of Extreme Rainfall

In Figure 2.2, we display the seasonal differences in the OER indicator between the I^+ and I^- phases compared to the I^N phases in percentage terms. The strongest link can be seen for NAO and EA. The mean OER per season and phase is displayed in Figure A6.1 in the appendix.

Extreme rainfall in winter occurs more frequently in southern and eastern Europe, and less frequently in northern countries during NAO$^-$; the opposite pattern is seen during NAO$^+$. In spring, during NAO$^-$ we observe more frequent extreme rainfall in large portions of eastern Europe. The main signal in summer and autumn is less frequent extreme rainfall, particularly in southern and eastern Europe during NAO$^+$. Extreme rainfall is less frequent in large part of Europe during EA$^-$, although more frequent extremes are seen in south-eastern regions. In winter and spring, we observe a higher OER in sparse areas of northern Europe during EA^+, and opposite pattern in southern and western Europe in all seasons.

In general, the influence of ENSO on the OER in Europe appears to be much smaller than the influence of NAO or EA. In winter, less frequent extreme rainfall is seen during $ENSO^-$ in sparse areas, particularly in the east. During spring, we observe positive differences in parts of northern Spain and southern France during $ENSO^-$, and over Sweden during $ENSO^+$. In autumn, we observe more frequent extreme rainfall in large areas of Europe within both phases of ENSO, especially in Iceland during $ENSO^+$.

In Figure 2.3, we show the significant differences in the IER for the I^+ and I^- phases compared to the I^N phases for each season in percentage terms. Again, NAO and EA show the strongest relationships. The mean IER per season and phase is displayed in Figure A6.2 in the appendix.

In winter during NAO^-, we observe higher IER in eastern Europe, and lower IER in northern and western Europe. The reverse pattern is observed during NAO^+. Except in winter during NAO^+, IER is lower in large areas of Europe. However, the opposite is observed in southeastern and northeastern Europe in summer during a NAO^-.

During EA^-, extreme rainfall is less intense over the year in northern and western Europe. In all seasons, we observe lower IER during EA^+ in large areas of the continent, except in summer and autumn in parts of northern and eastern Europe, where extreme rainfalls are on average 25% more intense.

In general, the influence of ENSO on the IER in Europe is limited and rather local. During $ENSO^-$, we observe lower IER in all seasons in scattered areas of western and eastern Europe, and higher IER over Spain during $ENSO^+$, except in autumn.

2.3.2 Anomalies in Flood Occurrence and Flood Damage at the pan-European scale

At the pan-European scale, all three indices of climate variability show significant relationships with Flood Occurrence in one or more phase and/or season (Figure 2.4a). The strongest link is observed for NAO. In summer, during NAO^+, anomalies in Flood Occurrence are 170% higher than during NAO^N. In winter, during NAO^-, anomalies in Flood Occurrence are on average 70% higher than during NAO^N. We also found that Flood Occurrence in spring is significantly lower during NAO^+, and higher (81% and 33%) during EA^+ and $ENSO^+$ but we find no significant anomalies during their negative phases.

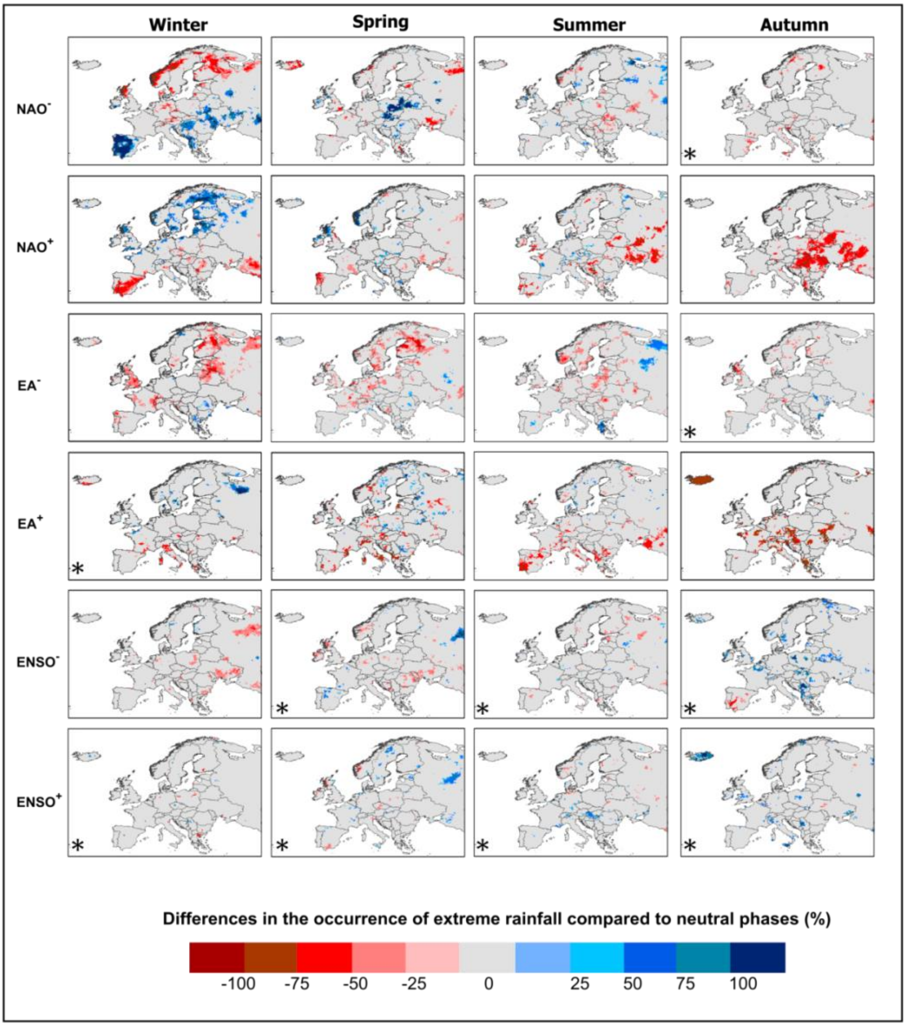

Figure 2.2 Mean percentage difference in the seasonal occurrence of extreme rainfall (OER) (number of events/season) between negative phase and positive phase of the indices of climate variability, compared to the neutral phase. Blue (red) colours symbolize a significantly higher (lower) number of extreme events compared to the neutral phase (each tail α= 5%). Field significance of the gridded results was assessed using the binomial distribution and found to be highly significant ($P < 0.001$). Seasons/phases of the indices of climate variability that were found to be significant only due to T-Test are indicated with an asterisk (*).

We find significant anomalies in Flood Damage (compared to I^N phases) linked to all three indices of climate variability, with the strongest anomalies again for NAO (Figure 2.4b). Anomalies in winter Flood Damage are on average 222% higher during NAO^-, and 104% lower in spring during NAO^+. Still in spring, Flood Damage is 137% higher during EA^-. We observe positive anomalies in summer

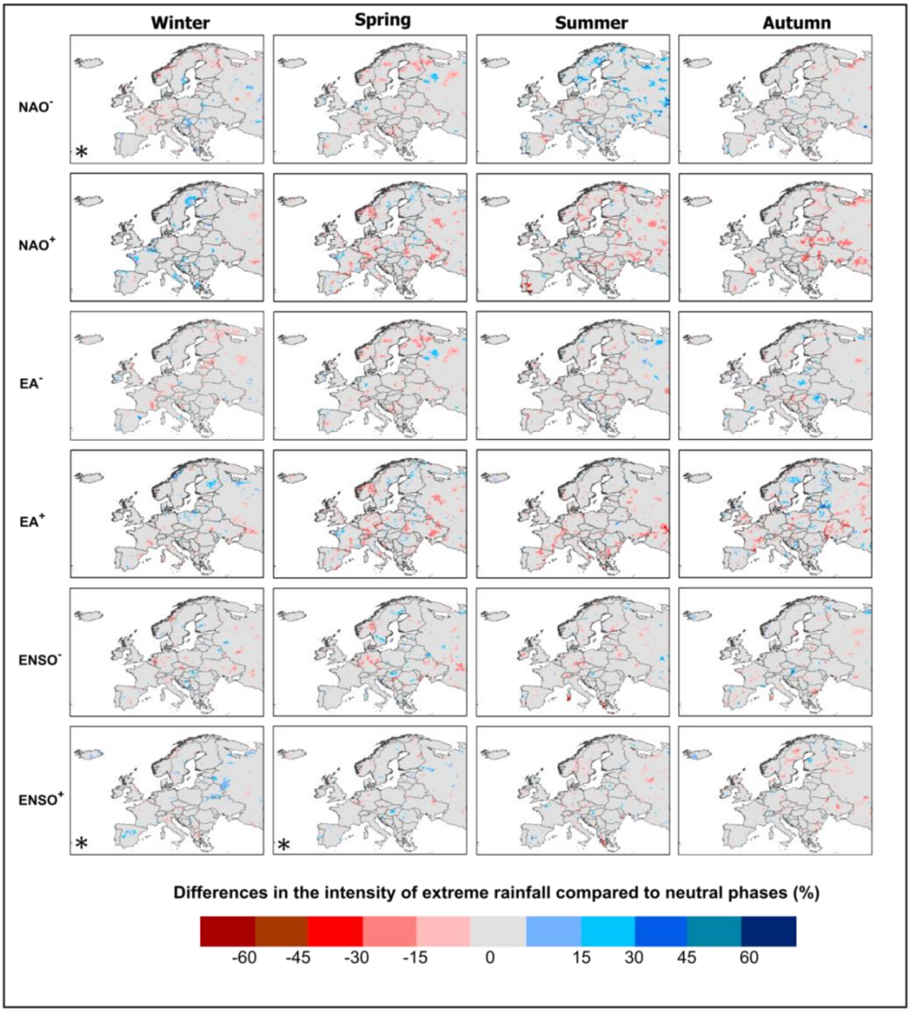

Figure 2.3 Mean difference in the intensity of extreme rainfall (IER) (mm/event) between negative phases and positive phases of the indices of climate variability, compared to neutral phases. Blue (red) colours symbolize significantly higher (lower) intensity of extremes events compared to a neutral phase (each tail α= 5%). Field significance of the gridded results was assessed using the binomial distribution and found to be highly significant (P < 0.001). Seasons/phases of the indices of climate variability that were found to be significant only due to T-Test are indicated with an asterisk (*).

during the positive phase of the NAO and ENSO, with the highest anomalies (374%) during NAO^+.

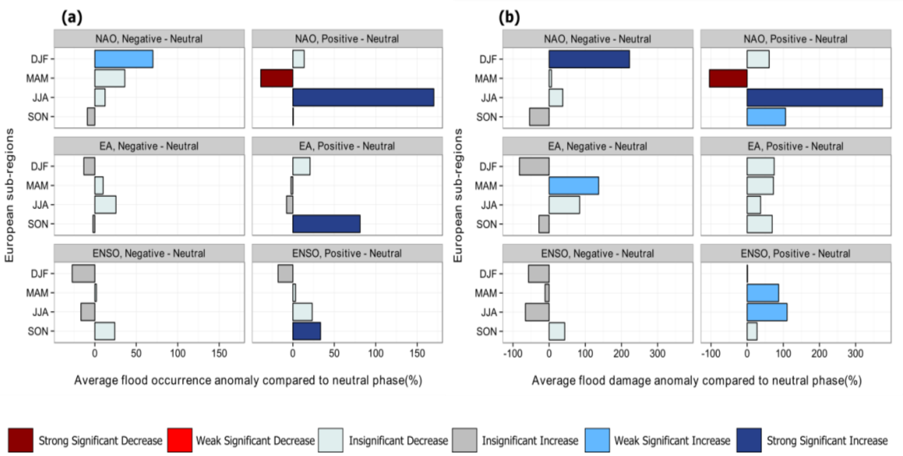

Figure 2.4 Pan-European analysis of the average percentage anomalies in (a) Flood Occurrence and (b) Flood Damage per season, during the positive and negatives phases of the different climate indices (compared to neutral). For strong significance, we use α= 5%, while for a weak significance α= 10% at each tail.

2.3.3 Anomalies in Flood Occurrence and Flood Damage at the sub-regional scale

In Figure 2.5, we show the anomalies in Flood Occurrence per season for the four European sub-regions. In southern Europe (Figure 2.5a), Flood Occurrence anomalies during winter are 181% higher during NAO$^-$, and 40% lower in spring during ENSO$^-$. In summer seasons Flood Occurrence anomalies are 111% higher during NAO$^+$, and 48% lower during EA$^+$ phases. However, anomalies in Flood Occurrence are 164% and 80% higher in autumn during EA$^+$ and ENSO$^+$, respectively.

For eastern Europe (Figure 2.5b), Flood Occurrence anomalies in winter are 89% and 59% higher during NAO$^+$ and EA$^+$, respectively. However, during NAO$^+$ in spring, Flood Occurrence is 47% lower compared to neutral, and 110% higher in summer. We found positive anomalies in Flood Occurrence in spring for NAO$^-$, and in autumn for ENSO$^-$.

In western Europe (Figure 2.5c), during NAO$^+$ in summer, Flood Occurrence is much higher (247%) compared to neutral. In addition, anomalies in Flood Occurrence in summer and autumn are on average 53% and 69% higher during EA$^-$ and EA$^+$.

In northern Europe (Figure 2.5d), in spring and summer, anomalies in Flood Occurrence are on average 47% and 62% lower during NAO$^+$ and ENSO$^+$, respectively. In addition, significant positive anomalies are seen in autumn during positive phases of ENSO and EA.

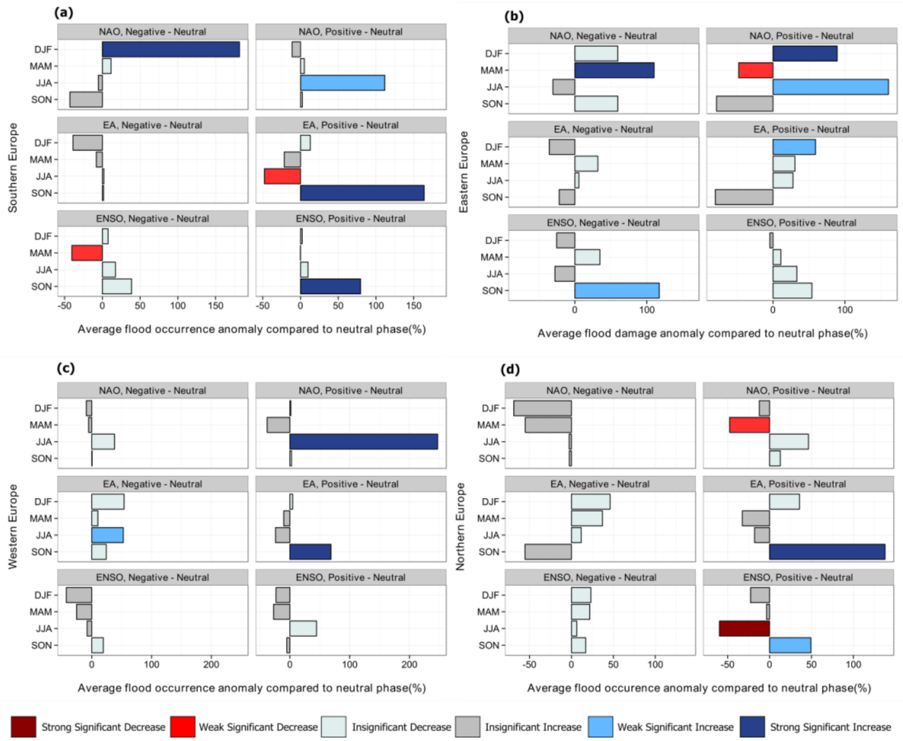

Figure 2.5 Average percentage anomalies in flood occurrence per season, within the positive and negative phases of the different climate indices (compared to neutral). Results are shown for: (a) southern Europe; (b) eastern Europe; (c) western Europe; (d) northern Europe. For strong significance, we use α= 5%, while for a weak significance α= 10% at each tail.

In terms of Flood Damage for southern Europe (Figure 2.6a), we find significant anomalies (compared to neutral) during several phases and/or seasons of the indices of climate variability. Anomalies in Flood Damage are positive (373%) in winter during NAO$^+$, and in summer (389%, 129% and 230%) for NAO$^-$ (389%), EA$^-$ (129%) and ENSO$^-$ (230%), respectively. Flood damages are lower during ENSO$^+$ in spring.

In eastern Europe (Figure 2.6b), we found significant anomalies in Flood Damage for one or more seasons or phases for all of the indicators of climate variability. Anomalies in Flood Damage are 120% in winter during EA$^+$, and 125% (277%) lower (higher) in spring during NAO$^+$ (EA$^-$). Flood Damages are 293% higher in summer during NAO$^+$, and –125% and 140% in autumn during the negative phases of ENSO and EA.

In western Europe (Figure 2.6c), we observe significant anomalies in Flood Damage during several phases and/or seasons of NAO and ENSO. In winter and summer, anomalies in Flood Damage are 107% and 400% higher during NAO$^+$, respectively. In summer and autumn, we find higher Flood Damage (121% and 157%) during ENSO$^+$ and ENSO$^-$.

In northern Europe (Figure 2.6d), spring and summer seasons are associated with negative anomalies in Flood Damage during the positive phases of the indices of climate variability. Anomalies in Flood Damage are higher in autumn (95% and 126%) during ENSO$^+$ and EA$^+$, respectively.

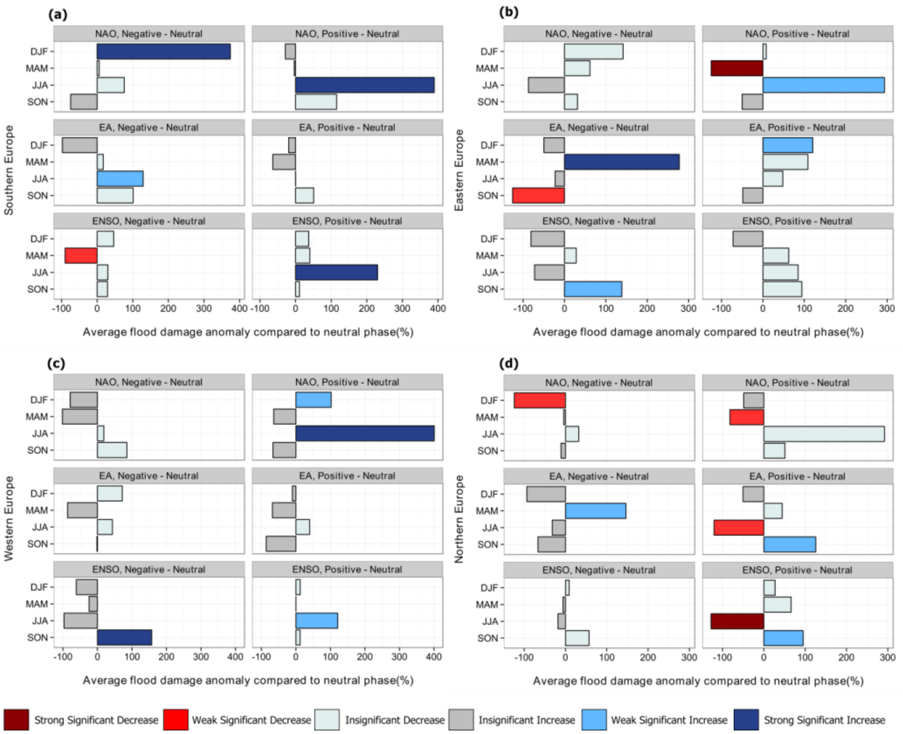

Figure 2.6 Average percentage anomalies in flood damage per season, within the positive and negative phases of the different climate indices (compared to neutral). Results are shown for: (a) southern Europe; (b) eastern Europe; (c) western Europe; (d) northern Europe. For strong significance, we use α= 5%, while for a weak significance α= 10% at each tail.

2.4 Discussion

2.4.1 Similarities and differences between the four flood indicators

We observe major similarities in the overall patterns among the four flood indicators. Large differences in OER and IER (Figures 2.2-2.3) often coincide with large anomalies in Flood Occurrence and Flood Damage (Figures 2.4-2.6 and appendix Table A7). For example, in winter southern- and eastern Europe receive more frequent and intense extreme rainfall during NAO^-. This may be causing the high anomalies in Flood Occurrence and Flood Damage at the pan-European scale. Floods, especially in summer, are greatly anomalous in eastern and western Europe, where more frequent events coincide with higher costs (appendix A3). Summer and autumn major floods in Europe are mostly driven by river and flash floods, which are triggered by regional heavy rainfall followed by consecutive wet days (Figure A5.2) (Barredo, 2007; Kundzewicz et al., 2005). For instance, in western and eastern Europe, regions where major European river basins are located, three of their most destructive floods occurred in summer caused by such weather conditions (Kundzewicz et al., 2005).

However, there are also some differences between the indicators. For example, for some regions/phases, floods events are not more frequent, but they are more damaging; this is the case in winter in western Europe during NAO^+. However, we note that this sub-region also shows more intense extreme precipitation in winter during NAO^+, which could result in larger floods and damages, even though the frequency of floods may not increase. Flood frequency can only partly explain anomalies in flood damage, and other drivers such as changes in exposure, vulnerability and intensity of extreme may also play a significant role. In addition, in some areas extreme rainfall is not more frequent, but more intense, as is the case in Scandinavian countries during NAO^- in summer. Additionally, some of the significant anomalies in Flood Damage may be influenced by a few exceptionally high damage events. For example, anomalies in Flood Damage during summer in southern Europe were heavily influenced by one single event in Italy in 2002, with an estimated US$ 5.5 bn in damages (35% of the total summer Flood Damage for the southern sub-region). Moreover, some high anomalies in Flood Occurrence may be related to other hydrometereological variables than IER and OER, such as snow melt and storm surge, which needs further study (Hall et al., 2014; Muis et al., 2016).

2.4.2 Comparison to previous research

We provide a detailed comparison between our results and those of past studies in Europe in A8 of the appendix. In brief, the following points can be summarised: (*i*) occurrence of winter extreme rainfall in southern regions is greatly related to NAO^-, while NAO^+ is linked to more frequent and intense extreme precipitation over northeastern areas, which agrees with previous studies e.g. (Lopez-Bustins et al., 2008; Quadrelli, Pavan, & Molteni, 2001; Rodó et al., 1997; Uvo, 2003); (*ii*) ENSO's influence on the European climate is not clear, and changes in the intensity and frequency of extreme precipitation are minor (Brönnimann, 2007; Frias et al., 2010; Rocha, 1999; Sun et al., 2015); (*iii*) in summer, we observe that NAO exerts great influence on rainfall patterns, but with an opposite sign to that observed in winter (Barnston & Livezey, 1987; Casanueva et al., 2014; Lorenzo et al., 2008); (*iv*) in autumn, extreme precipitations are less frequent and intense during NAO^+, which are associated with drier conditions over southern and eastern regions, as highlighted by others (Casanueva et al., 2014).

Another aspect that affects susceptibly to climate-related disasters is the level of flood protection. According to a modelling study (Scussolini et al., 2015), large portions of southern and eastern Europe are protected against floods up to about a 20-year return period. Consequently, many locations are not well adapted to deal with extreme flood events. This has been the case in Italy and Spain, which have previously suffered major flash floods and river flood disasters (Barredo, 2007). The high levels of flood protection in northern Europe (Scussolini et al., 2015), may reduce the influence of climate variability on Flood Occurrence and Flood Damage.

Socioeconomic development also plays a role in flood risk, and may alter the relationship between hydrometeorological extremes and resulting losses (Jongman et al., 2015). Only few studies analyzed changes in vulnerability, flood damage and risk due to the lack of reliable and long flood damage data (Merz et al., 2012). However, some studies found that changes in exposure and socioeconomic development are a key drivers of increasing flood losses in Europe (Barredo, 2009; Llasat et al., 2008). Others have suggested that increased flood damage is also associated with increased precipitation (Pielke Jr & Downton, 2000). Therefore, understanding trends in flood frequency and damage can only be partially explained by estimating meteorological changes.

2.4.3 Applications, limitations and recommendations

The indices of climate variability assessed in this study can be forecast with varying levels of skill and lead-times. Hindcasts of winter-mean NAO show that there is skill for predicting this index with lead-times of at least a month (Scaife et al., 2014; Smith et al., 2016). EA summer and autumn anomalies can be properly forecast with a lead-time of 1 to 2 months (Iglesias et al., 2014). ENSO forecasting is more developed, and most prediction systems have some skill to detect events with lead-times of 12–14 months (Gonzalez & Goddard, 2016). In those regions of Europe where ENSO, NAO and EA show strong relationships with precipitation and flood indicators, seasonal risk outlooks could potentially be developed based on predicted values of the indices of climate variability. Such outlooks could provide information on whether flood impacts in upcoming seasons are likely to be higher or lower than average, which could be useful for flood disaster preparedness. For example, the European Union's Solidarity Fund, holding 500 million Euros per year to help member states finance disaster losses, is greatly affected by large-scale correlations in flood losses (Jongman et al., 2014). Taking into account some of the long term climate variability anomalies in the design and budgetary planning of international finance mechanisms could reduce the chance of such a fund facing unexpected pay-outs across large regions in Europe, and reduce the chance of fund depletion.

The primary limitation of this investigation is that we analyse the impact of ENSO, NAO and EA separately. Globally, ENSO is the main driver of interannual climate variability, but interactions between ENSO and both NAO and EA have been identified in several studies e.g. (Greatbatch, 2004; Iglesias et al., 2014; Rodríguez-Fonseca et al., 2016). Future work should assess the joint impacts of ENSO, NAO and EA on floods. Future work would also benefit from using different methods to classify the different phases of climate variability, and examining time lags between the indices of climate variability on the flood indicators. For instance, ENSO's impact on climate may vary throughout its developing, mature or decaying phases (Huang et al., 2012; Ronghui & Yifang, 1989; Wang & Gu, 2016; Zhang, Sumi, & Kimoto, 1999). Moreover, some of the significant results may had occurred by random chance on season/phases of the indices of climate variability marked with an asterisk on Figures 2.2 and 2.3, where results would improve with a local analysis. Furthermore, global disaster databases, such as the one used in this study, are also know to face major limitations, such as reporting errors (Kron et al., 2012). Lastly, extreme rainfall frequency and intensity, and large-scale climate variability can only partly explain anomalies in flood risk (Barredo, 2009; Pielke Jr & Downton, 2000). Other aspects such as changes in exposure and vulnerability (Jongman et al., 2015; Scussolini et al., 2015) were not included in this study.

2.5 Conclusions

In this paper, we examined relationships between the different phases of ENSO, NAO and EA, and differences and anomalies in the OER, IER, Flood Occurrence, and Flood Damage. We show that:

- Positive and negative phases of NAO and EA are associated with more frequent extreme rainfall over large areas of Europe. The NAO^+ and EA^+ phases are associated with less frequent extreme rainfall, especially during summer and autumn.

- Positive and negative phases of NAO and EA are associated with significant differences in the intensity of extreme rainfall compared to the neutral phase.
- The effect of ENSO on the intensity and frequency of extreme rainfall in Europe is much smaller than the influence of NAO or EA.
- At the aggregated pan-European scale, NAO, EA and ENSO show significant relationships with Flood Occurrence and Flood Damage in one or more phases and/or season. In summer during NAO^+, these anomalies are on average 170% and 136% higher.
- Anomalies in Flood Damage in spring and summer are on average 110% lower in northern Europe during NAO^+, EA^+ and $ENSO^+$.
- Flood Damage and Flood Occurrence are strongly related with climate variability, especially in southern and eastern Europe.

Therefore, when investigating at the Pan-European scale, all three indices of climate variability should be taken into account. Future work should focus on their mutual relations to flood risk. Consequently, the inclusion of seasonal forecasts of the indices of climate variability could be used to develop flood risk outlooks for the continent.

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